REDUCING THE RISKS OF SPENT POWER REACTOR FUEL IN THE UNITED STATES

Robert Alvarez
Senior Scholar
Institute for Policy Studies
Washington, D.C.

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The nuclear crisis at the Daiichi complex in Fukushima, Japan has turned a spotlight on the dangers of spent nuclear fuel in pools.

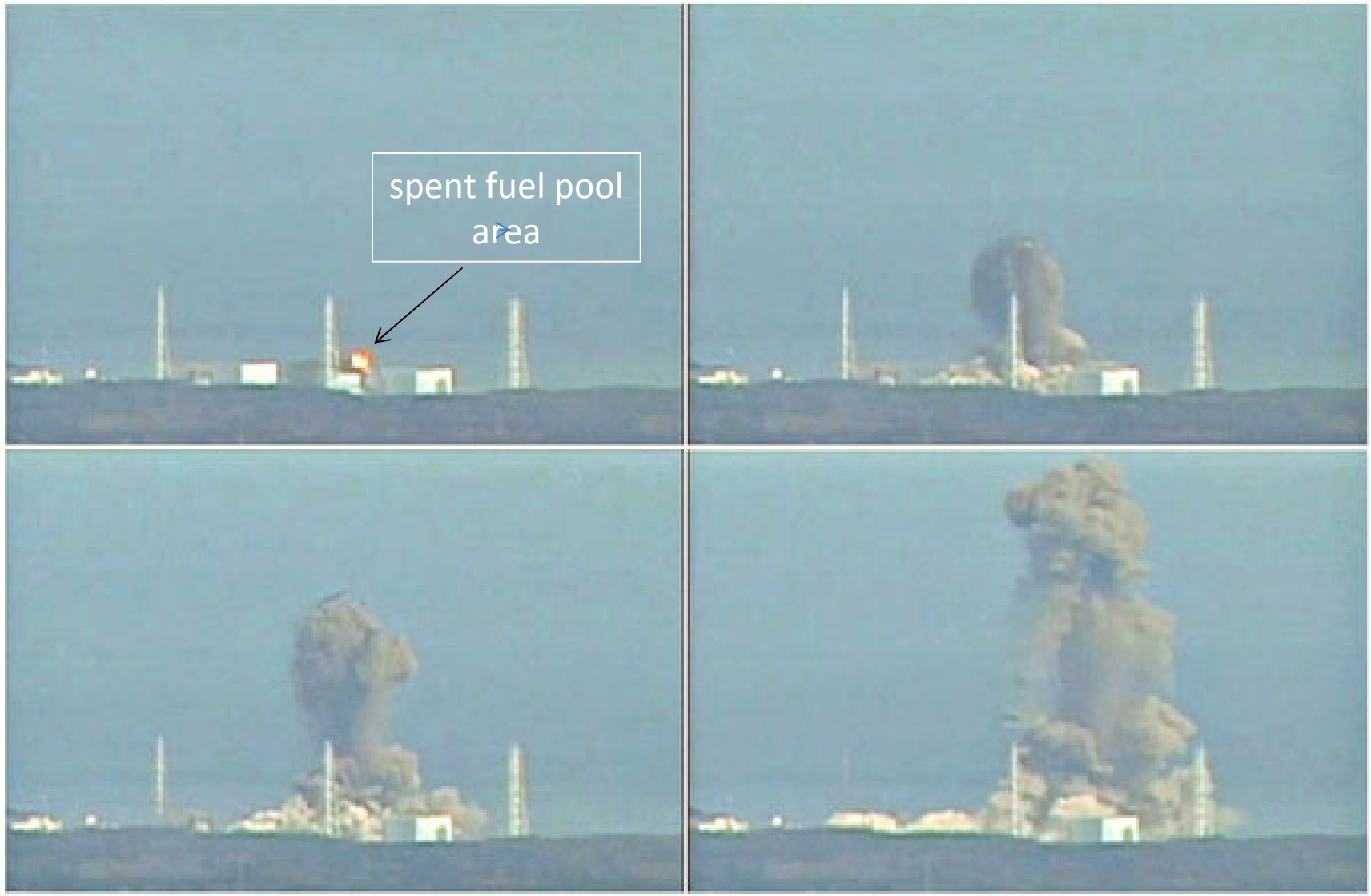


Source: http://cryptome.org/eyeball/daiichi-npp/daiichi-photos.htm

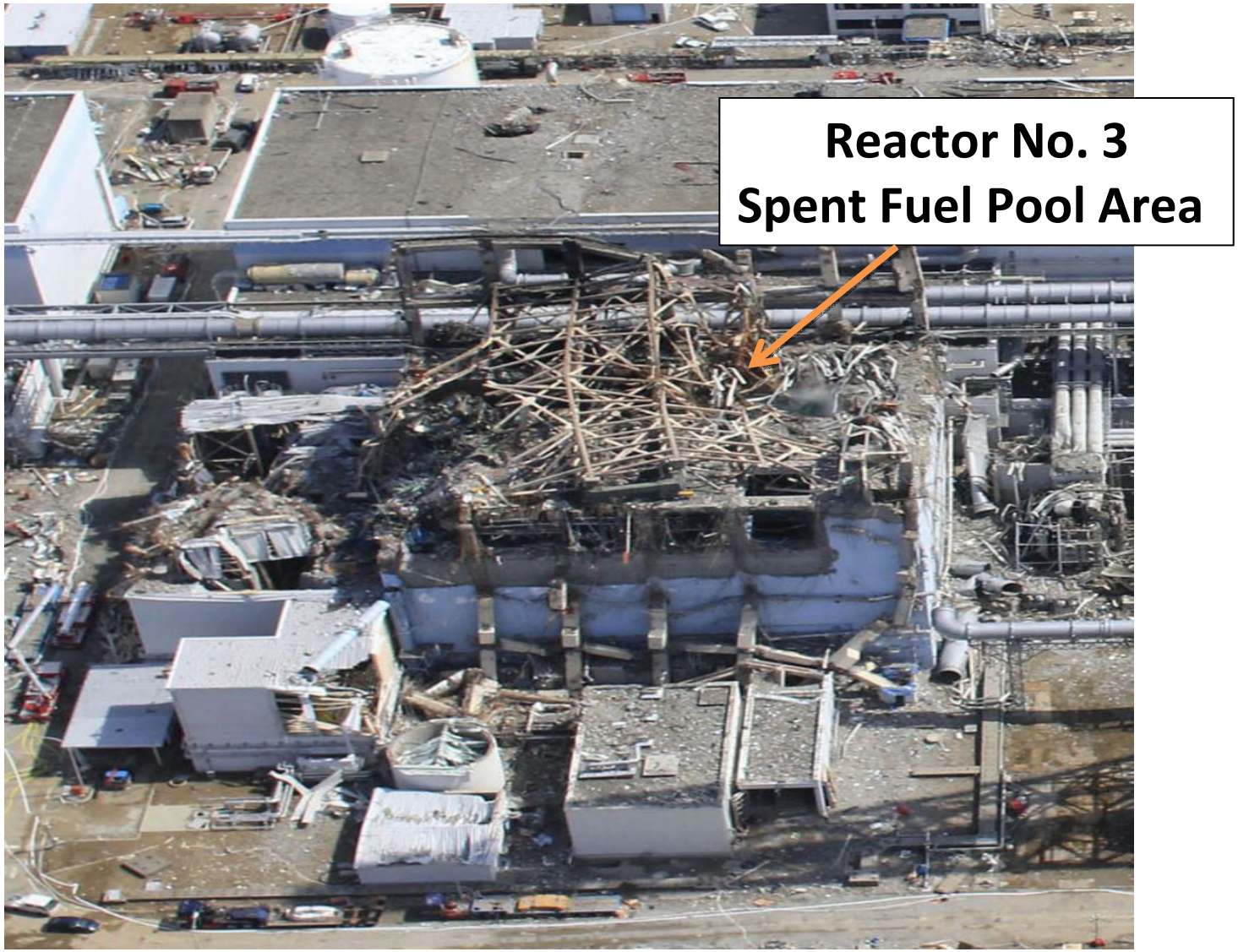
Radiation dose rates in the vicinity of the pools were life-threatening and required remotely-controlled water cannons in an attempt to restore lost water.

Explosion Sequence at Reactor No. 3

March 13, 2001



Source: Associated Press/NTV.



Source: Air Photo Service Co. Ltd., Japan, March 24, 2011



Source: Abc Tv/EPA



Source: Associated Press

What Happened at Dia-Ichi Unit No. 4 Pool?

" *The fuel pool is really two pools separated by a gate. Fuel removed from the reactor goes first into the small, upper pool which is only 20 or 25 feet deep* [emphasis added]. Later they move the fuel to the big, deep pool.

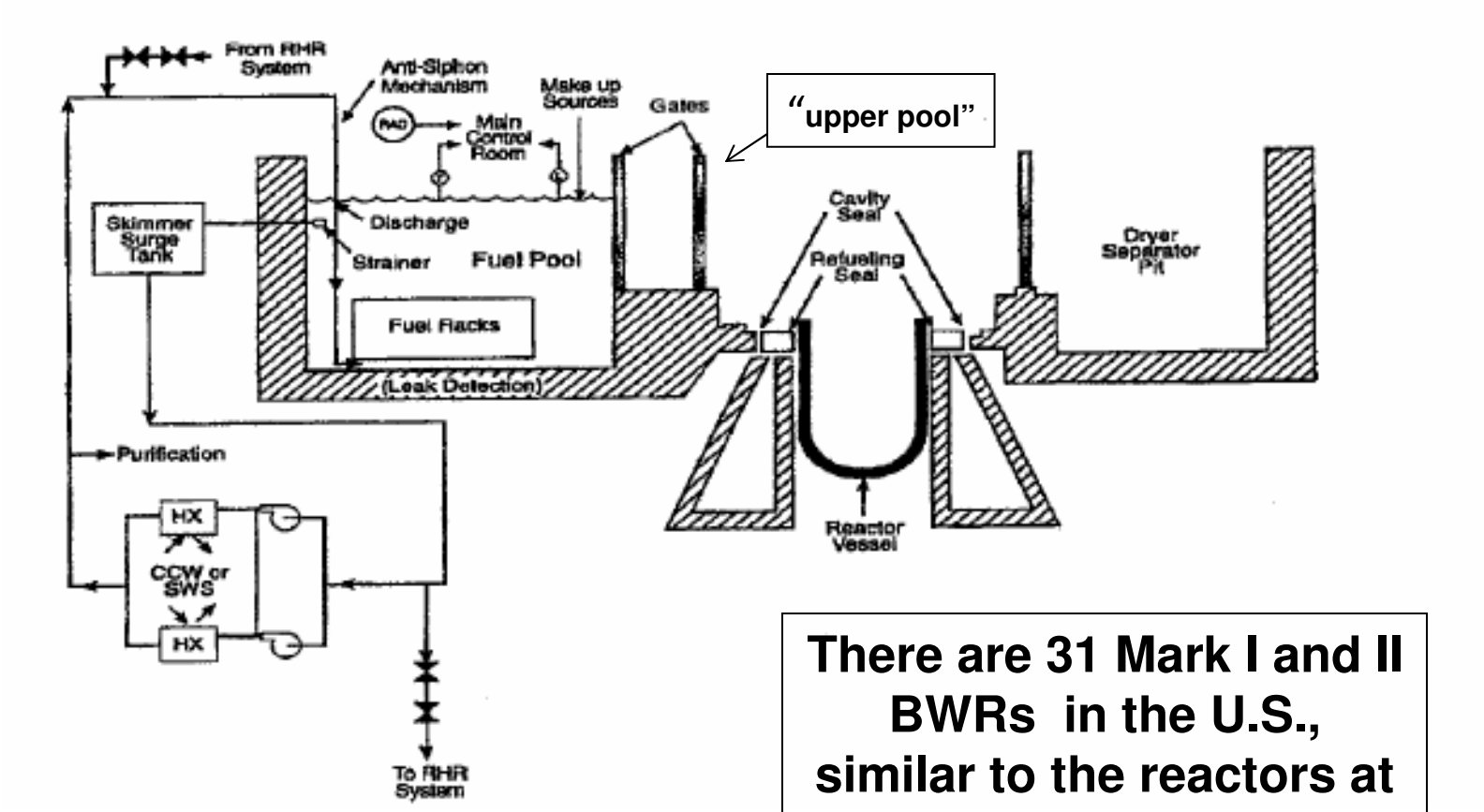
*There was apparently only a little fuel in this upper pool at the time of the quake. This **UPPER** pool broke. The three-eighths inch steel liner is cracked and will not hold water. The concrete wall in front of this upper pool fell off. Fuel was severely damaged probably by explosion* [emphasis added]. Temperature profiles measured by helicopters show clumps of hot stuff that must be fuel scattered around the floor area. This scenario is consistent with the numerous reports of fire in unit 4.

This is a real nightmare. But the main fuel pool in unit 4 appears intact and full of water. The spread of radioactivity came fortunately from a small amount of fuel."

FUKUSHIMA NUCLEAR ACCIDENT

THE KEESE SCHOOL OF CONTINUING EDUCATION
MURRAY E. MILES MARCH 24, 2011

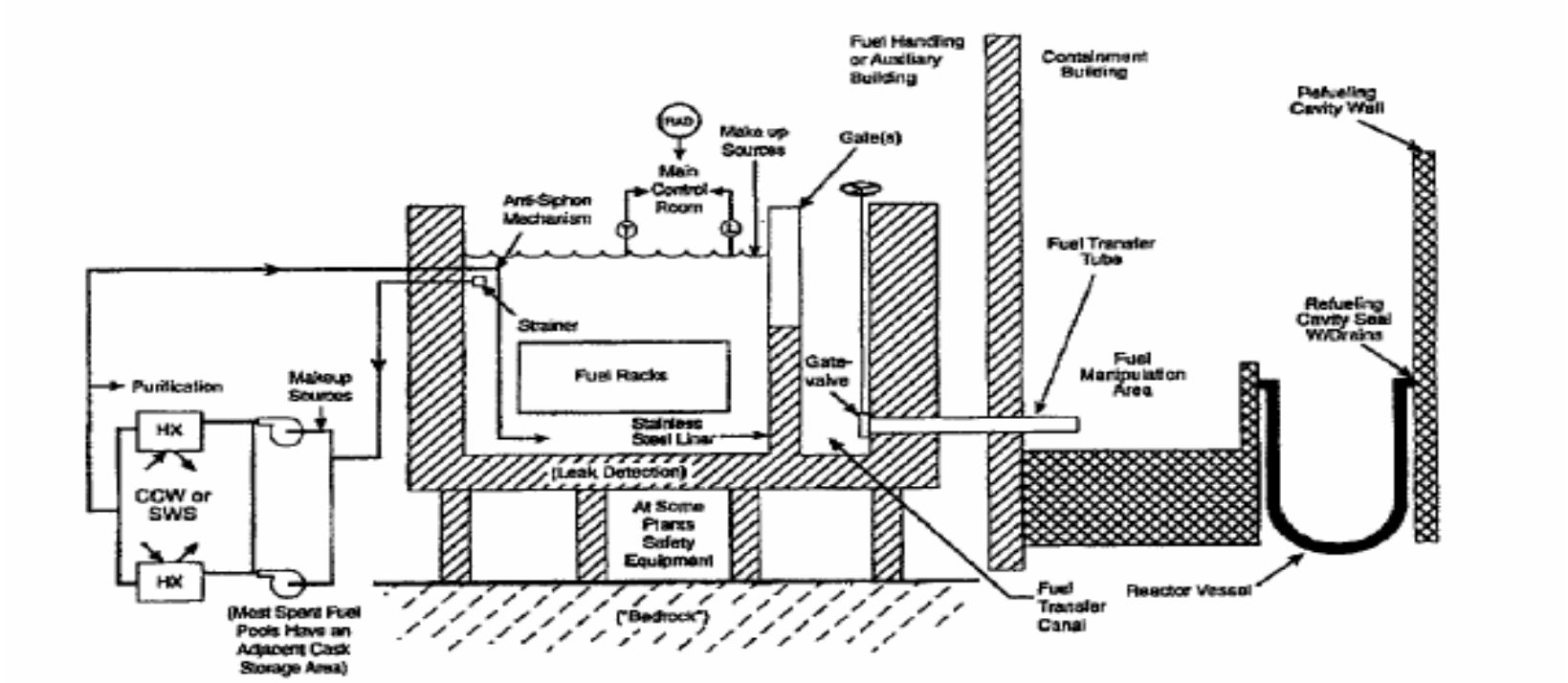
Layout of spent fuel pool and transfer system for boiling water reactors (BWR)



Source: U.S. Nuclear Regulatory Commission, NUREG-1275.

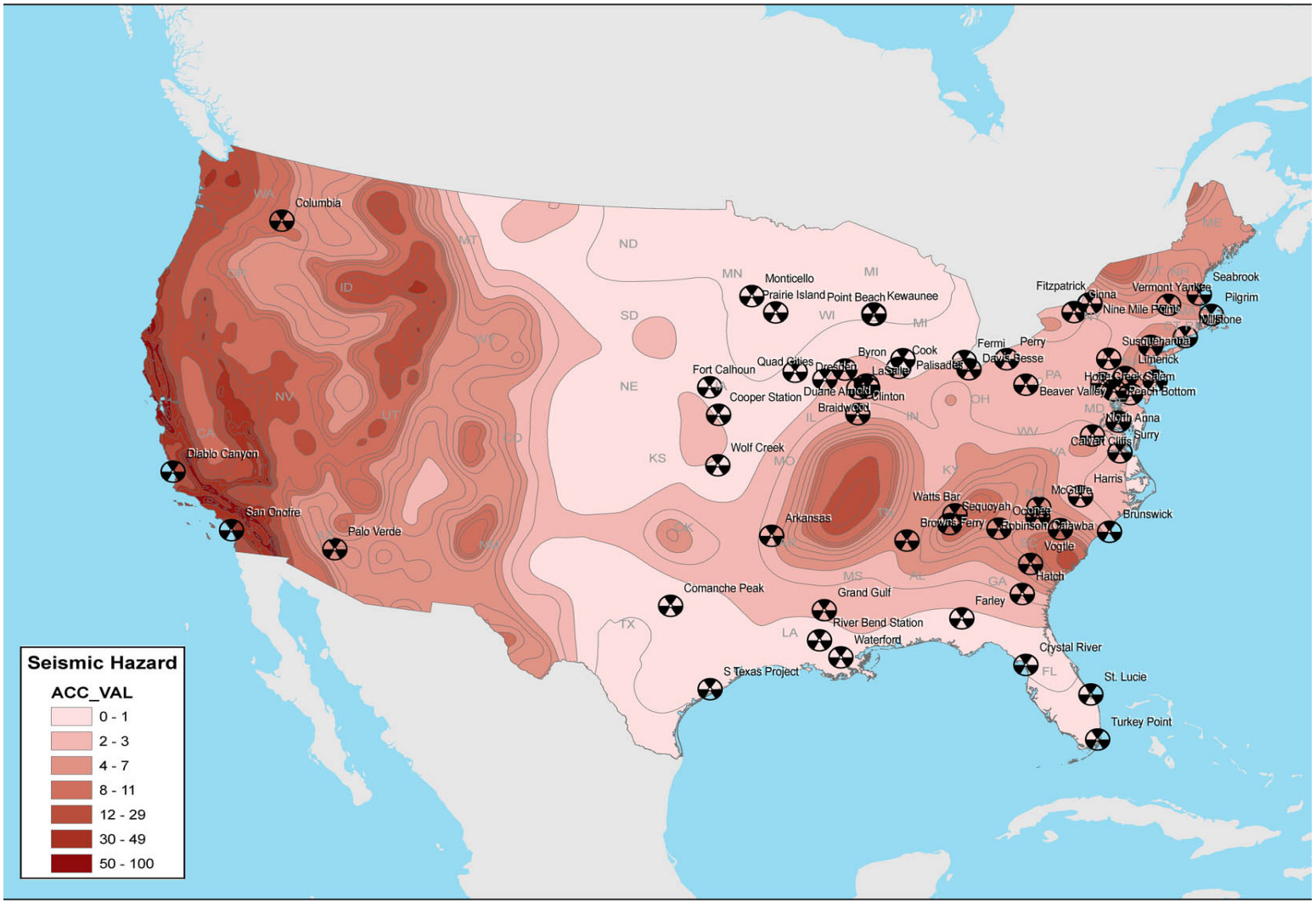
There are 31 Mark I and II BWRs in the U.S., similar to the reactors at Fukushima, with spent fuel pools ~100 feet above ground.

Layout for spent fuel pool and transfer system for pressurized water reactors



Source: U.S. Nuclear Regulatory Commission, NUREG-1275.

U.S. Nuclear Power Reactors in Earthquake Zones



Source: Greenpeace

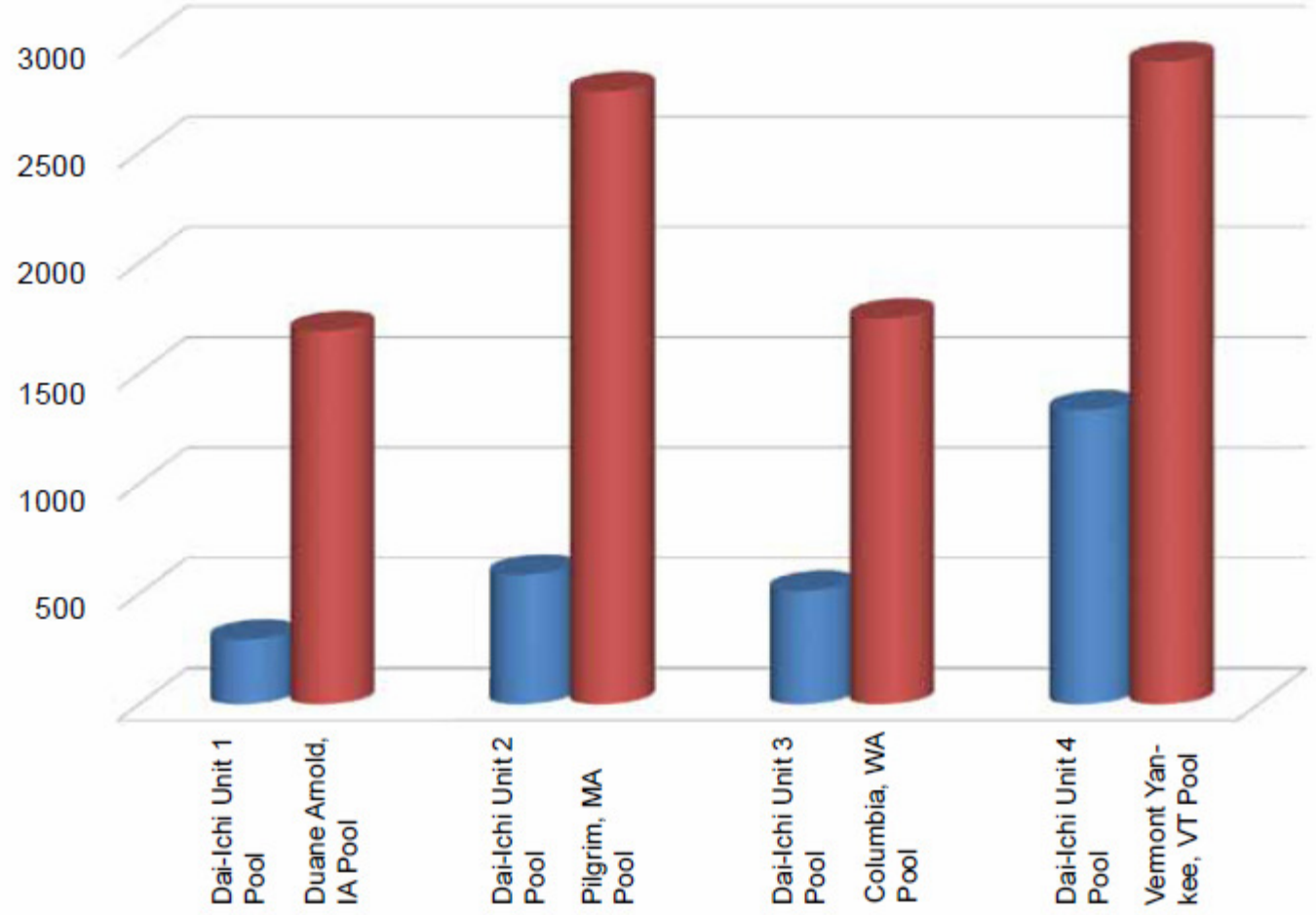
High Density Power Reactor Spent Fuel Pool

The U.S. Nuclear Regulatory Commission permits U.S. Spent reactor fuel pools to hold, on the average, four to five times the amount in the Fukushima reactors.



Like the Fukushima reactors,
U.S. spent fuel pools are located outside of the containment structure that holds the reactor pressure vessel

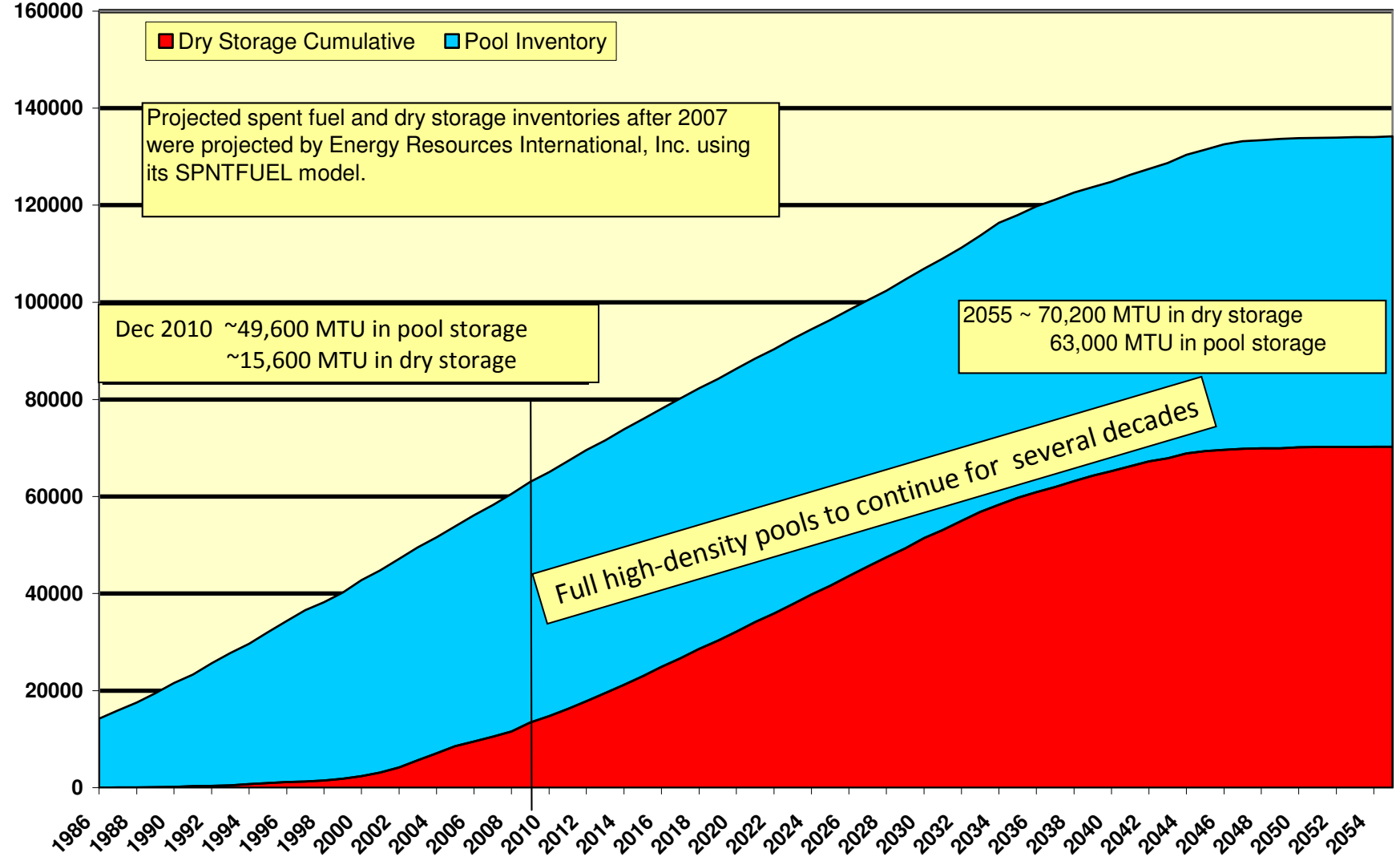
Spent Fuel Assemblies in Pool at the Dai-Ichi Nuclear Site in Fukushima and individual Boiling Water Reactors in the United States



Sources: All Things Nuclear, Union of Concerned Scientists, March 21, 2011; NEI, March 2011; DOE/EIS-0250, Appendix A, Table A-7, Energy NW, March 29, 2011.

CUMULATIVE US COMMERCIAL SPENT NUCLEAR FUEL INVENTORY (1986 to 2055)

SPENT NUCLEAR FUEL (Metric Tons Uranium) **Total Radioactivity (Dry/Wet) = ~27 billion Curies**



By 2055: >485,000 assemblies (per ACI Nuclear Energy Solutions)

Adapted from Kessler/EPRI - June 2010

Regulation of Spent Fuel Pools: Criticality Safety

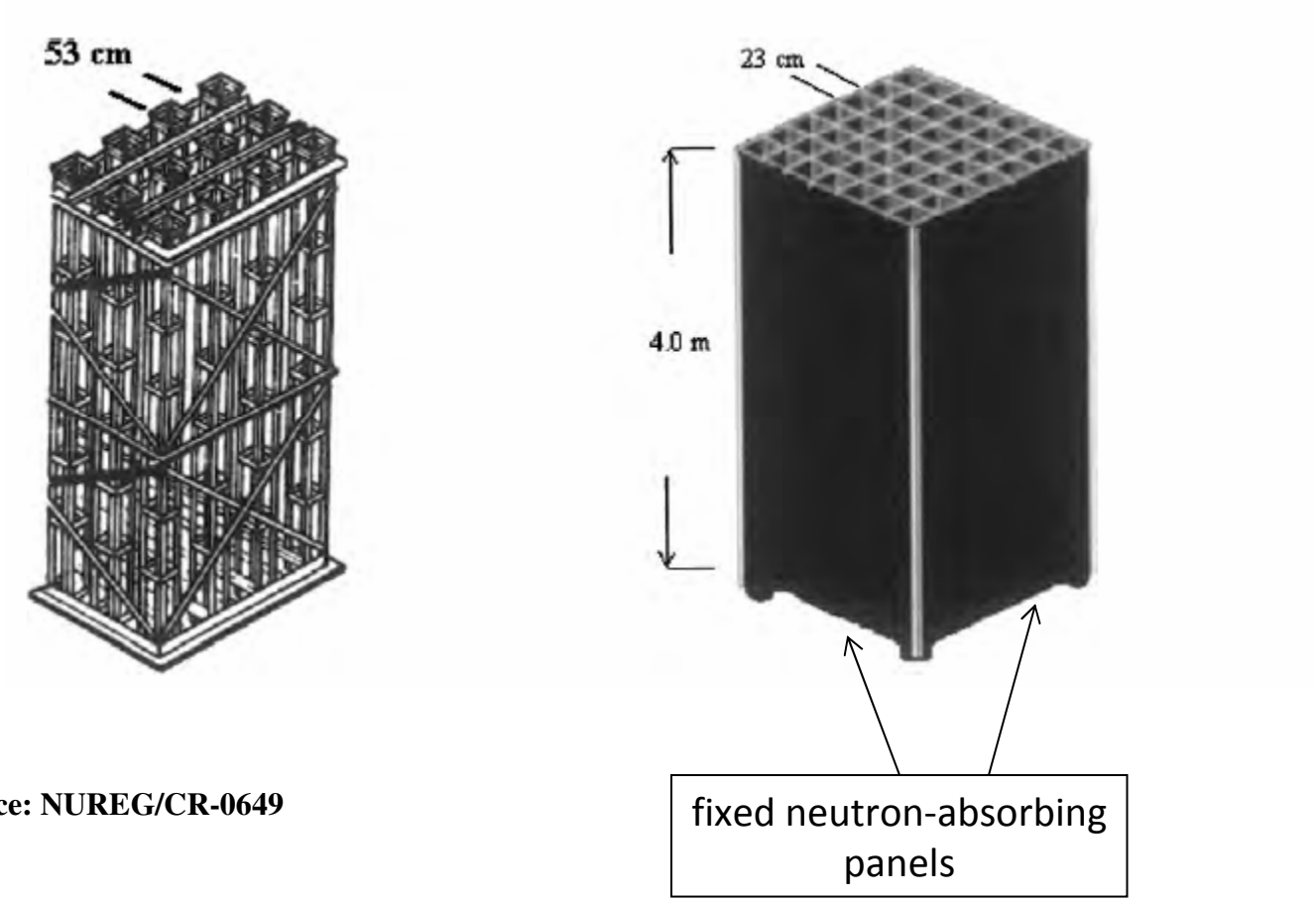
" The conservatism/margins in spent fuel pool (SFP) criticality analyses have been decreasing. …*Fuel assemblies themselves have become more reactive*… *Unfortunately, virtually every permanently installed neutron absorber, for which a history can be established, has exhibited some degradation. Some have lost a significant portion of their neutron absorbing capability. In some cases, the degradation is so extensive that the permanently installed neutron absorber can no longer be credited in the criticality analysis* [Emphasis added]"

U.S. NRC, On Site Spent Fuel Criticality Analyses NRR Action Plan May 21, 2010

Some 50 U.S. reactor sites utilize fixed neutron absorbing panels. With plant life extension these panels which originally had a design life of 40 years, will be in service more than 60 years.

In 2010 it was discovered that Florida Power and Light failed to report that it exceeded its spent fuel pool criticality safety margin for five years due to deterioration of neutron absorbers at the Turkey Point reactor near Miami.

Open and dense-pack PWR spent fuel racks



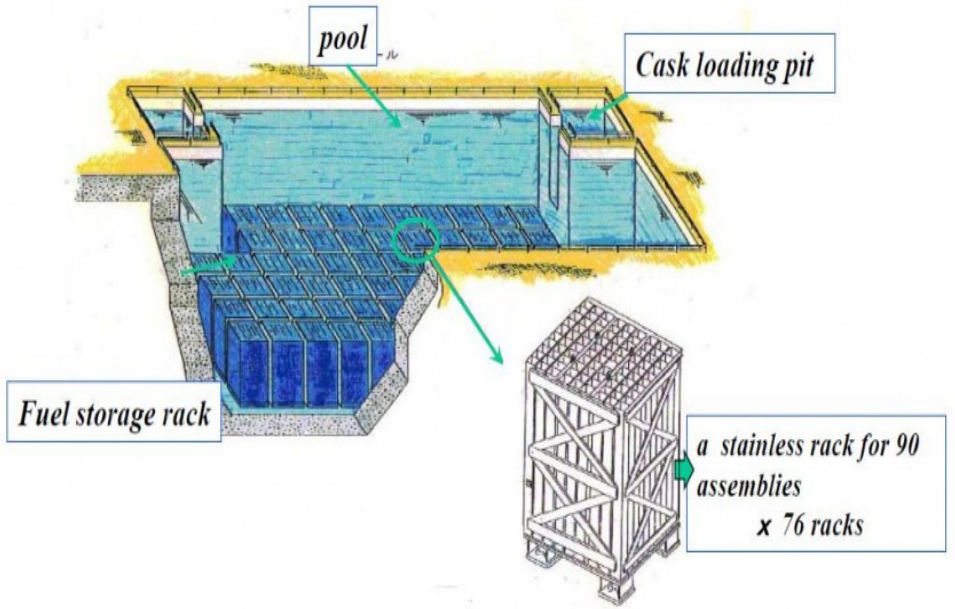
Source: NUREG/CR-0649

Regulation of Spent Fuel Pools: Leaks

Over the past 30 years, there have been at least 66 incidents at U.S. reactors in which there was a significant loss of spent fuel water.

Ten have occurred since the September 11, 2001 terrorist attacks, after which the government pledged that it would reinforce nuclear safety measures.

Seven losses of cooling water were from pool liner leaks



The majority of the losses occurred through connective systems involving the transfer of spent fuel from the reactor or to casks.

Large losses also occurred though gates and seals connected to the fuel cavity pool in which spent fuel is discharged.

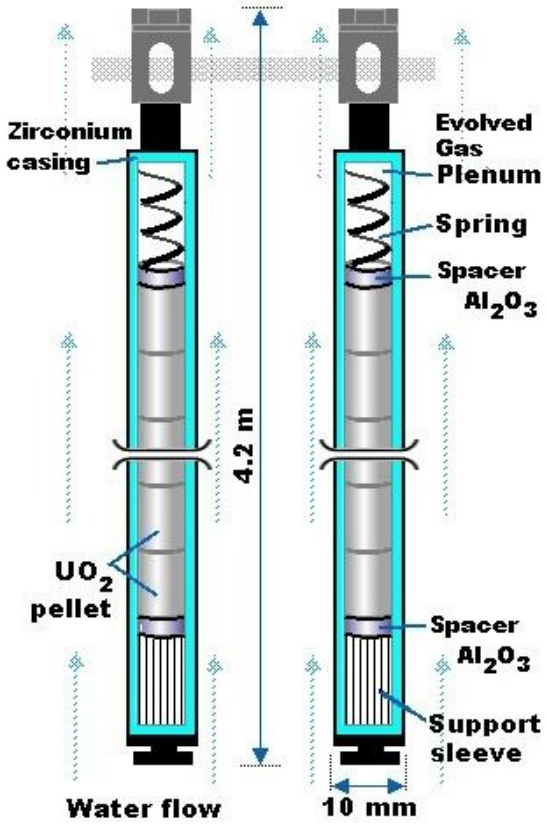
High burnup increases stress on pool cooling/cleaning systems and fuel rod cladding.

•Reactor owners have increased the level of uranium-235 to allow for longer operating periods.

•Reactor operating cycles have been doubled from 12 to 24 months in order to generate more electricity.

•More spent fuel with higher radioactivity and thermal heat is being off-loaded into evermore-crowded pools during each refueling outage.

•Pool cooling and cleaning systems are under greater strain -- making spare pumps and heat exchangers operate far longer than originally intended.



•Reactor fuel cladding is less than one millimeter thick (thinner than a credit card) and is one of the most important barriers preventing the escape of radioactive materials.

•Higher burnup of reactor fuel can cause the cladding to thin and become brittle.

•It also builds higher pressure from hydrogen and fission gases within the cladding, and increases risk of failure.

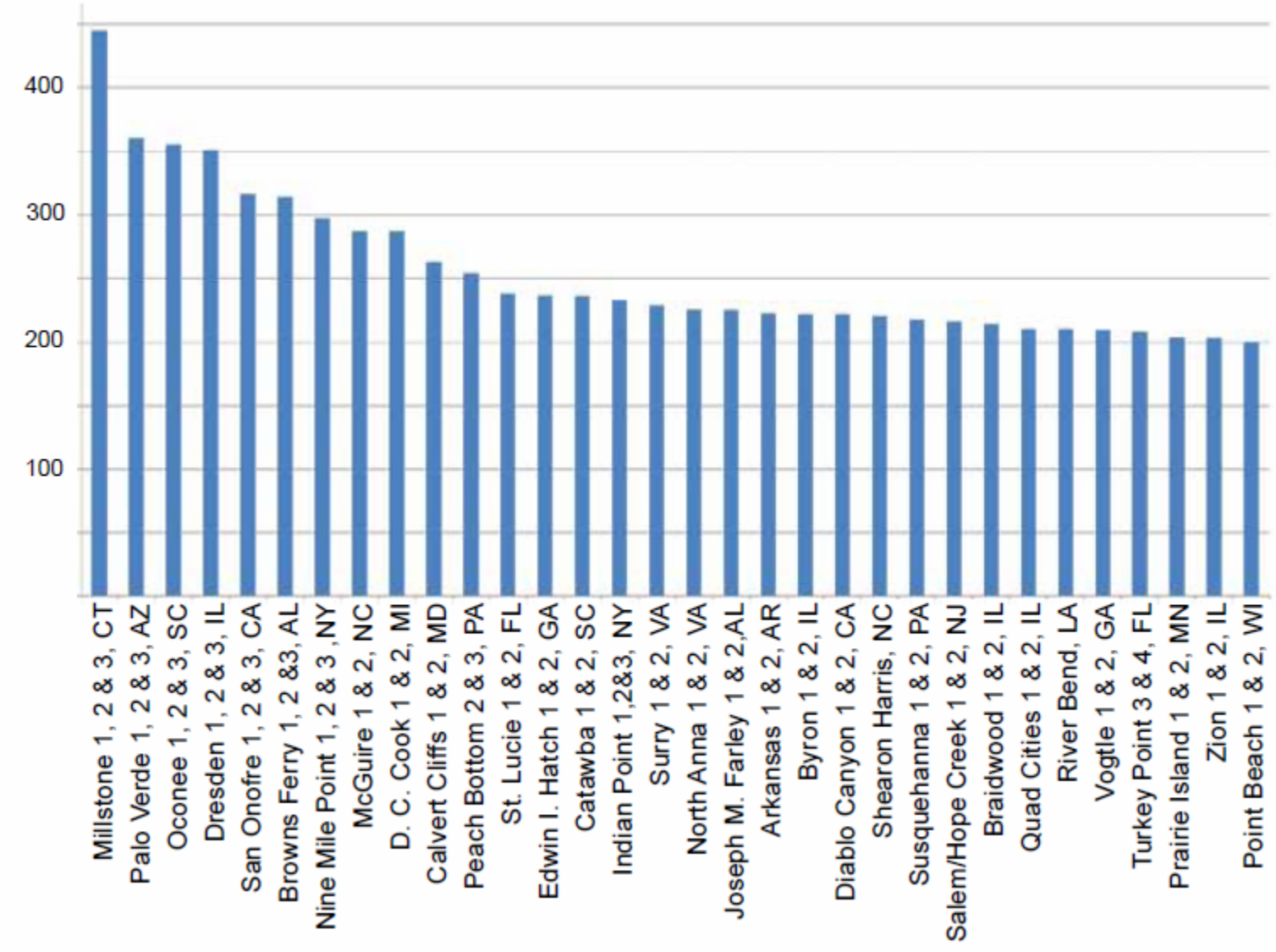
• Impacts of high burnup on the integrity of zircalloy cladding is not well understood.

Isotope	Half Life (yrs)	Radioactivity (Ci)
Hydrogen-3	12.3	10,200,000
Carbon-14	5,700	95,000
Chlorine-36	300,000	750
Iron-55	2.7	420,000
Cobalt-60	5.3	27,000,000
Nickel-59	76,000	160,000
Nickel-63	100	22,000,000
Selenium-79	64,000	30,000
Krypton-85	10.7	150,000,000
Strontium-90	29	3,000,000,000
Zirconium-93	1,500,000	160,000
Niobium-93m	16	110,000
Niobium-94	24,000	56,000
Technetium-99	210,000	950,000
Ruthenium-106	1	4,700
Palladium-107	6,500,000	8,800
Cadmium-133m	14	1,500,000
Antimony-125	2.8	3,600,000
Tin-126	1,000,000	59,000
Iodine-129	17,000,000	2,400
Cesium-134	2.1	5,800,000
Cesium-135	2,300,000	36,000
Cesium-137	30	4,500,000,000
Promethium-147	2.6	18,000,000
Samarium-151	90	25,000,000

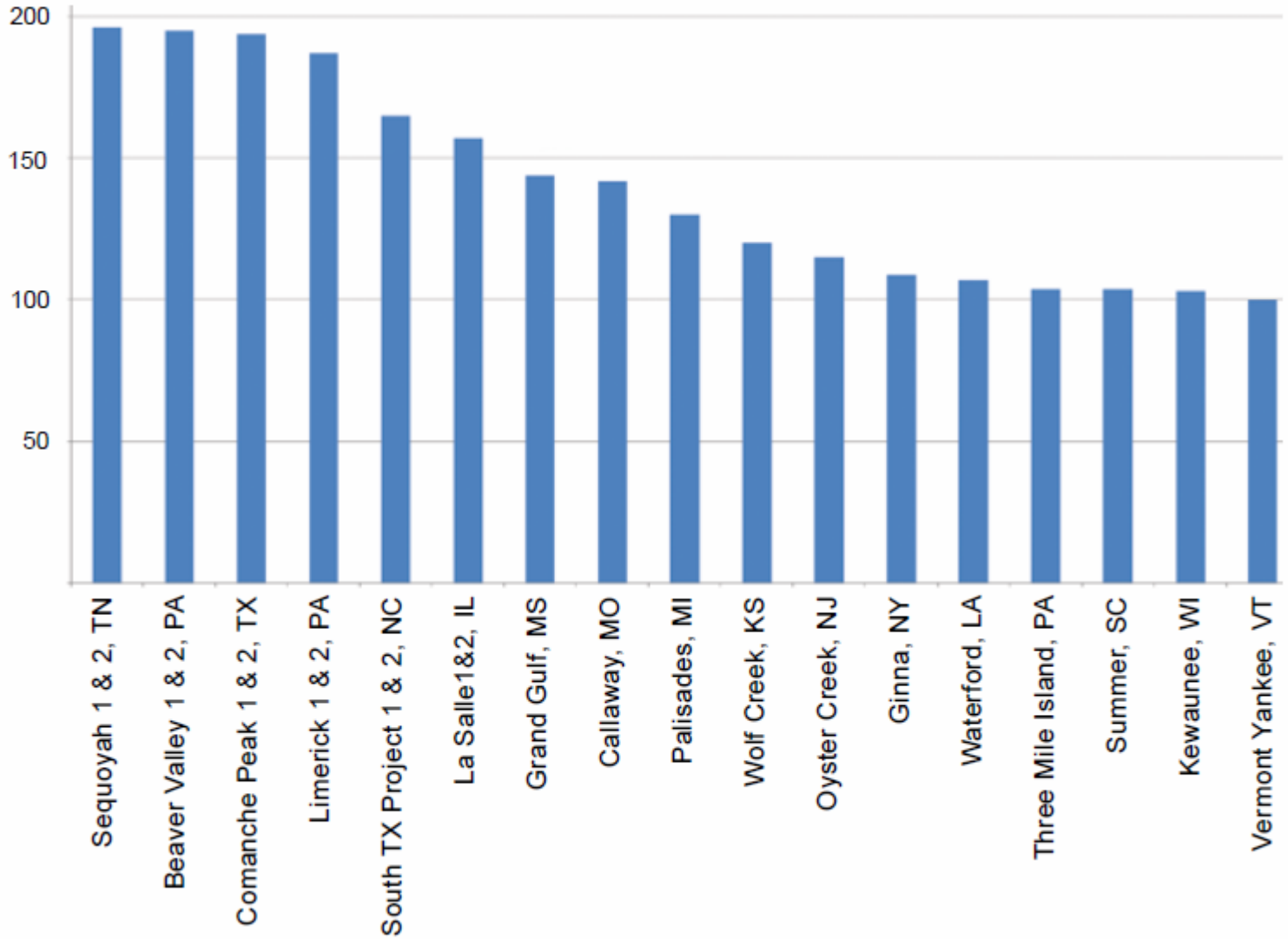
Isotope	Half Live (yrs)	Radioactivity (Ci)
Europium-154	8.6	120,000,000
Europium-155	4.8	22,000,000
Actinium-227	2.2	0.97
Thorium-230	75,000	18
Protactinium-231	33,000	2.1
Uranium-232	69	2600
Uranium-233	160,000	3.9
Uranium-234	250,000	84,000
Uranium-235	720,000,000	1,000
Uranium-236	23,000,000	18,000
Uranium-238	4,500,000,000	20,000
Plutonium-241	14	3,200,000,000
Plutonium-238	88	240,000,000
Americium-241	430	220,000,000
Curium-244	18	120,000,000
Plutonium-240	6,500	36,000,000
Plutonium-239	24,000	24,000,000
Americium-243	7,400	1,900,000
Americium-242/242m	140	1,600,000
Curium-242	0.45	1,300,000
Curium-243	29	1,300,000
Plutonium-242	380,000	140,000
Neptunium-237	2,100,000	30,000
Curium-245	8,500	29,000
Curium-246	4,800	6,300
		~12 billion Ci

Source: DOE/EIS-0250 Appendix A.

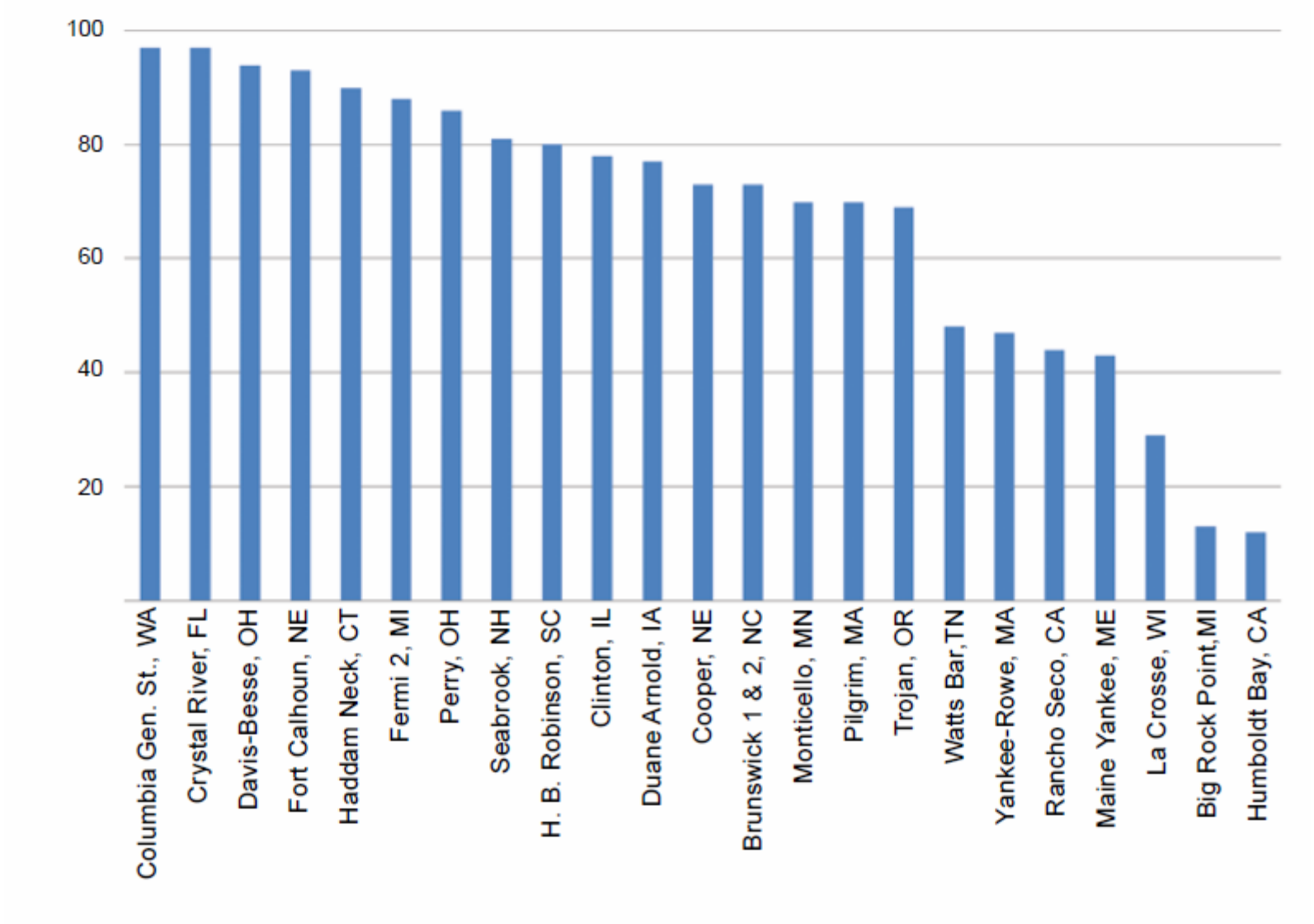
Spent Power Reactor Fuel Inventories Greater than 200 million Curies



Spent Power Reactor Fuel Inventories Between 100 and 200 million Curies



Spent Power Reactor Fuel Inventories Between 10 and 100 million Curies



- About 4.5 billion curies, roughly 40 percent of the U.S. spent fuel inventory, is cesium-137.

- With a half-life of 30 years, Cs-137 gives off potentially dangerous external penetrating radiation.

- Cs-137 mimics potassium as it accumulates in the food chain.

- There is about four to five times the amount of cesium-137 than in reactor cores.

- Spent fuel at U.S. nuclear reactors contains roughly 20 times more cesium-137 than was released by more than 650 atmospheric nuclear weapons tests throughout the world.

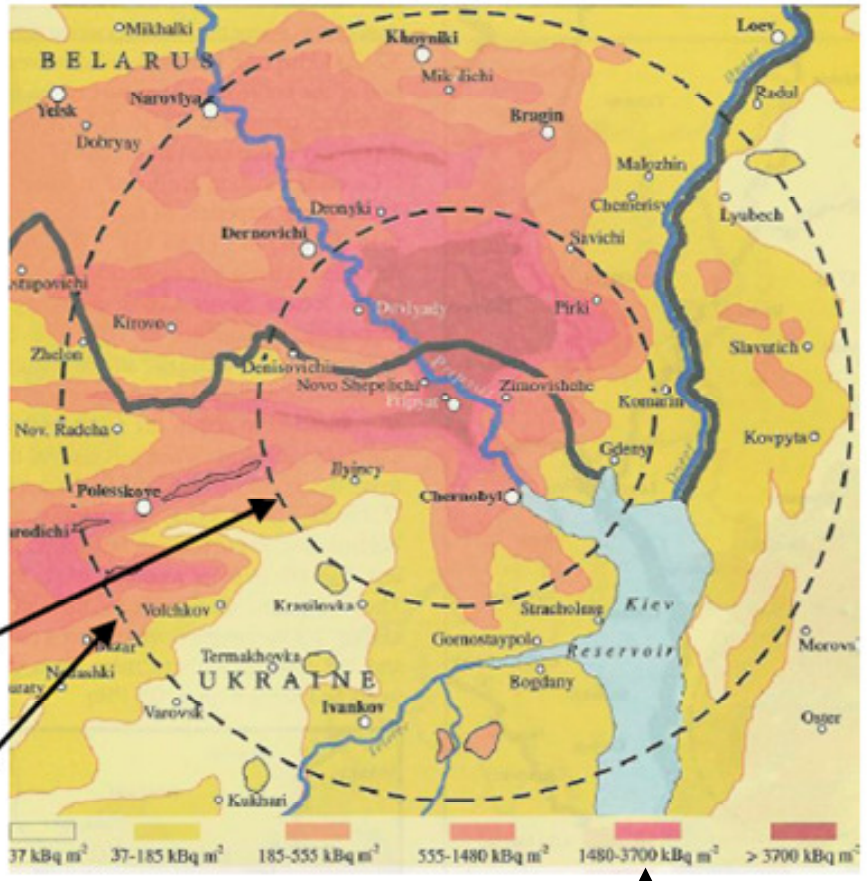
2 MCi of Cs^{137} (30-year halflife) released by Chernobyl

>15 Ci/km²: radiation control area: > 10,000 km² (1/2 of area of NJ)

>50 Ci/km²): >0.7% chance of radiation-caused cancer death from lifetime external radiation ~ 3100 km²

18-mile radius (permanently evacuated)

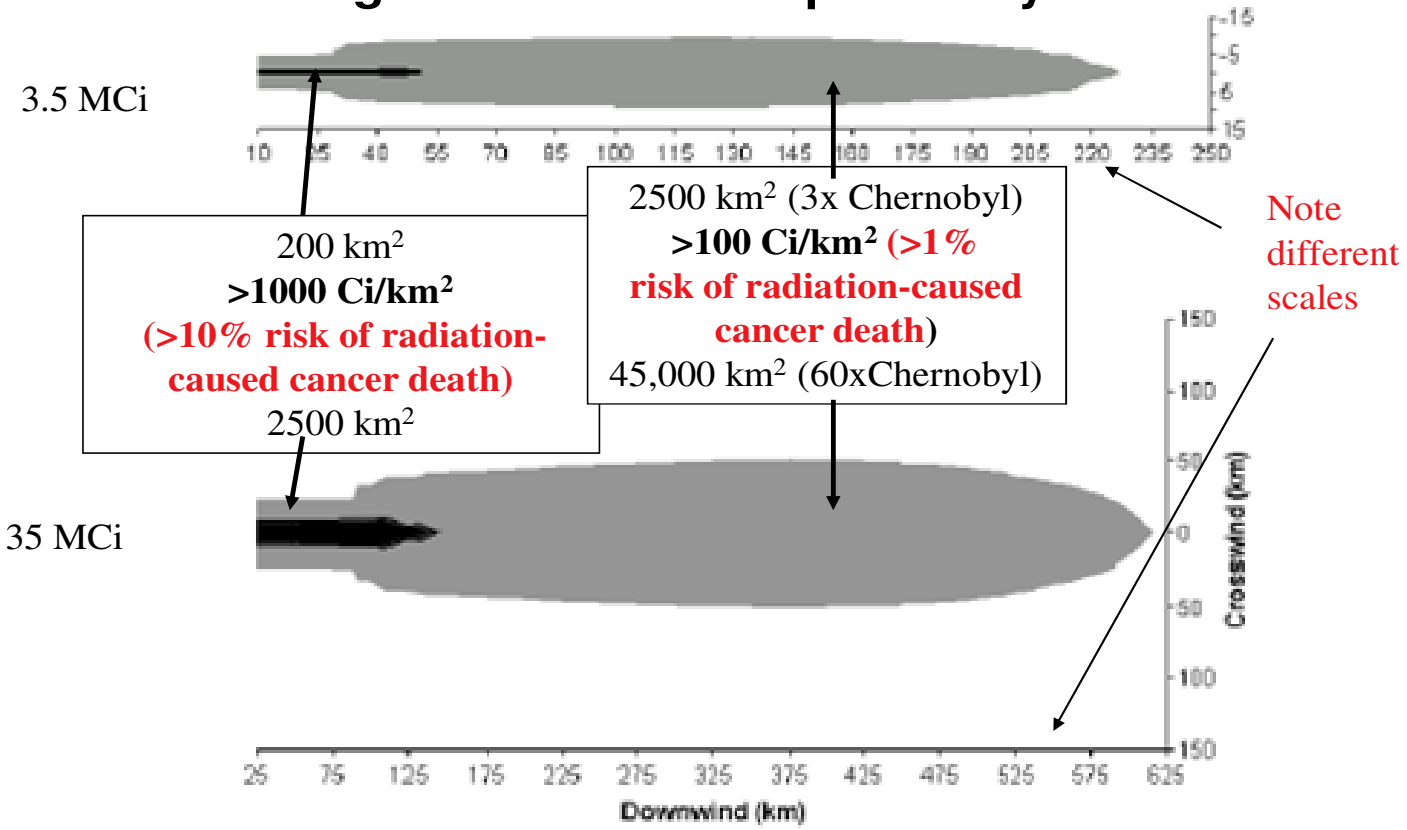
36-mile radius



(UNSCEAR-2000)

50 MCi/km²

MACCS2 code prediction for smoldering pool fire releasing ^{137}Cs into a 10 mph steady wind



Source: F. von Hippel, presentation to NAS, February 12, 2004

National Research Council Findings Regarding Vulnerabilities of Reactor Spent Fuel Pools

"A loss-of-pool-coolant event resulting from damage or collapse of the pool could have severe consequences…

It is not prudent to dismiss nuclear plants, including spent fuel storage facilities as undesirable targets for terrorists…

under some conditions, a terrorist attack that partially or completely drained a spent fuel pool could lead to a propagating zirconium cladding fire and release large quantities of radioactive materials to the environment…

Such fires would create thermal plumes that could potentially transport radioactive aerosols hundreds of miles downwind under appropriate atmospheric conditions."

National Research Council, Committee on the Safety and Security of Commercial Spent Nuclear Fuel Storage, "Board on Radioactive Waste Management," (2006)

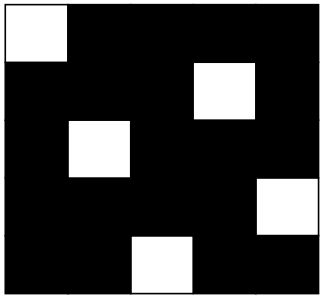
Damage estimates for 3.5-35 MCi Cs-137 release

Site	Damages ($B)	Cancer Deaths
Catawba	76-547	3100-7700
Indian Point	145-461	1500-5600
LaSalle	54-80	2100-6400
Palo Verde	11-80	600-2000
Three-Mile Is.	171-568	2300-7000
Average	**91-347**	**1900-5700**

Source: F. von Hippel, presentation to NAS, February 12, 2004

Why reduce storage density?

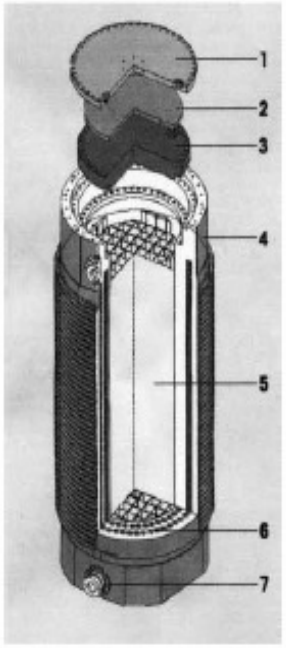
- Reduces the risk of ignition.
- Would allow open-rack storage of hottest fuel or
- Removal of one fifth of fuel assemblies could expose at least one side of each to an open channel



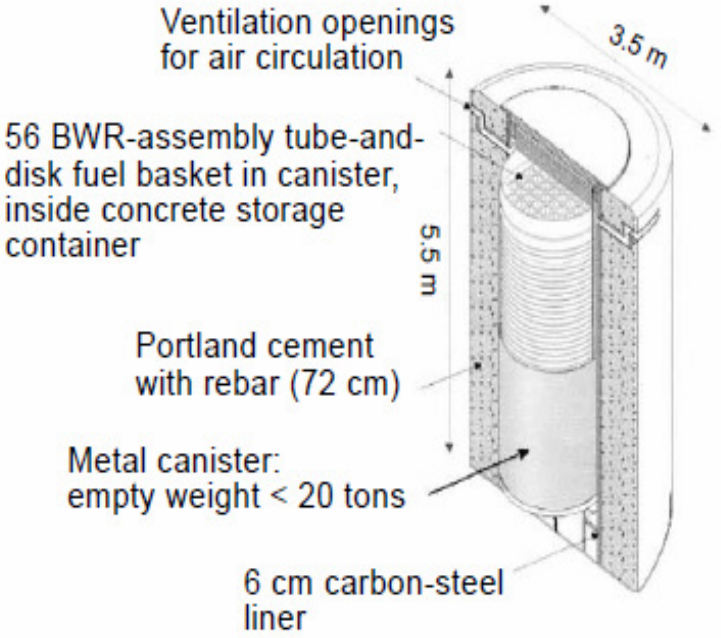
Two Types of Dry Storage Casks

Castor V/52

1. Secondary Lid
2. Neutron Moderator Plate
3. Primary Lid
4. Cask Body with Cooling Fins
5. Fuel Assembly Basket
6. Neutron Moderator Rods
7. Trunnion



Holtec



Solid cast iron steel shell shielded by concrete

Magnitude of Task

- **49,620 metric tons of dense-packed fuel currently in pools**

- **10,000 tons with more than five years cooling could be stored in about 10,000 casks**

- **15,573 metric tons in dry storage.**

- **Two major U.S. manufacturers have said they could ramp up their combined production to 500 casks/yr.**

The risk of densely-packed fuel pools in the U.S. can be significantly reduced by placing spent fuel older than five years into dry, hardened storage containers –something Germany did 25 years ago.

$1-2 million per cask =>$1-2 billion for 1000 casks

Cost of dry storage

0.04- 0.7 cents per kWh generated from the fuel (less than 1% of retail price of electricity in U.S.)

Money could also be allocated from $18.1 billion in unexpended funds already collected from consumers of nuclear-generated electricity under the Nuclear Waste Policy Act to establish a disposal site for high-level radioactive wastes.

Conclusion

After more than 50 years, the quest for permanent nuclear waste disposal remains illusory.

One thing, however, is clear: the largest concentrations of radioactivity on the planet will remain in storage at U.S. reactor sites for the indefinite future.

In protecting America from nuclear catastrophe, safely securing the spent fuel by eliminating highly radioactive, crowded pools should be a public safety priority of the highest degree.

With a price tag of as much as $7 billion, the cost of fixing America's nuclear vulnerabilities may sound high, especially given the heated budget debate occurring in Washington. But the price of doing too little is incalculable.